RESEARCH MEMORANDUM

INVESTIGATION OF EFFECT OF NUMBER AND WIDTH OF ANNULAR

FLAME-HOLDER GUTTERS ON AFTERBURNER PERFORMANCE

By James G. Henzel, Jr., and Lively Bryant

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

The effect of the number and width of annular flame-holder gutters on afterburner performance was investigated in a 26-inch-diameter afterburner test rig. The burner inlet temperature was held at 1250° F. A 1-ring, a 2-ring, and two 3-ring flame holders were investigated over a range of fuel-air ratios from about 0.03 to about 0.10. For these conditions, afterburner inlet total pressures varied from about 450 to 1300 pounds per square foot absolute.

In general, the combustion efficiency increased as the number of annular gutters increased. A 3-ring, 48-percent blockage flame holder had 15 to 20 percentage points higher efficiency than a 1-ring, 23-percent blockage flame holder for burner inlet total pressures from about 600 to 800 pounds per square foot absolute over a range of fuel-air ratios from 0.05 to 0.07. In this investigation gutter widths of 1.5 inches or more appeared necessary for good low pressure performance. Below a burner inlet total pressure of about 700 pounds per square foot absolute a 2-ring, 1.5-inch-width V-gutter flame holder was superior to a 3-ring, 0.75-inch-width V-gutter flame holder because of local blowout of the flame seating on the 0.75-inch V-gutters. The flame seating on the 1.5-inch V-gutters remained bright and steady. If nonburning total-pressure losses in excess of 2 percent are to be avoided, afterburner flame-holder blockages should not exceed about 35 percent for burner inlet velocities greater than 500 feet per second.

INTRODUCTION

Afterburners used for thrust augmentation during certain periods of flight operation require high combustion efficiency over a wide range of pressures and stable combustion over a wide range of fuel-air ratios. Low internal pressure losses are desirable during nonafterburning operation for efficient aircraft cruise. One of the components affecting the performance of an afterburner is the flame holder, which provides

the sheltered zone necessary for ignition and combustion stabilization
of the fuel-air mixture. In reference 1, the shape of the flame holder
was shown to have little influence on both combustion efficiency and
stability limits. Studies of flame propagation, such as those in ref-
erence 2, imply that the number of flame-holder gutters might, however,
have an important effect on the combustion efficiency. Also, in ref-
erence 3·it is stated that the number and width of the flame-holder gut-
ters influenced the combustion efficiency and stability limits,
respectively.

A brief investigation was therefore conducted to determine di-
rectly the effects on the combustion efficiency, stability limits, and
burner total-pressure loss of the number and width of flame-holder an-
nular gutters. The data presented in this report were obtained by op-
erating the 26-inch-diameter afterburner of reference 1 in the direct-
connect facility. The burner inlet temperature was maintained at
1250° F. A 1-ring, a 2-ring, and two 3-ring flame holders were inves-
tigated over a range of fuel-air ratios from about 0.03 to about 0.10.
For these conditions afterburner inlet total pressures varied from
about 450 to 1300 pounds per square foot absolute.

APPARATUS

Installation

The general arrangement of the afterburner installation together
with a detailed sketch of the burner is shown in figure 1. Combustion
air entered the preheater at a temperature of approximately 80° F and
was heated to a temperature of 1250° F. The preheater was composed of
eight J-35 combustor cans and simulated a primary turbojet engine com-
bustor. Upon leaving the preheater the air entered a mixing chamber
where it was thoroughly diffused to provide a uniform temperature dis-
tribution. A 44 percent solidity screen was placed at the diffuser en-
trance to promote a uniform velocity profile of the air passing from the
mixing chamber into the diffuser. The diffuser inner body was designed
for a constant rate of area increase except at the discharge end, where
the rate of change increased because of the rounded-off end of the inner
body. The inner body was supported by four streamlined struts 90°
apart. The flame holders were placed 7 inches downstream of the end of
the inner body and were mounted in an accessible spool piece to facili-
tate the installation of the different flame holders. This spool piece
contained a quartz window which provided a means of observing the flame
front during combustion and of recording blow-outs. The combustion
chamber was 25.75 inches in diameter and 48 inches long. The exhaust
nozzle was of the convergent-divergent type and had an area ratio (ratio
of nozzle throat area to burner cross-sectional area) of 70 percent.
The nozzle was designed to remain choked down to an over-all pressure

ratio (ratio of nozzle inlet pressure to nozzle exhaust pressure) of 1.25; the divergent section was used to induce choking at the throat under some conditions of marginal exhaust system capacity.

The fuel injection system for this investigation consisted of 24 radial spray bars equally spaced circumferentially and installed in the diffuser section. The fuel was injected 29.5 inches upstream of the flame holder and normal to the direction of the air flow. Each fuel spray bar contained eight orifices, four on each side, which were 0.020-inch in diameter. The arrangement of the bars is shown in figure 2.

Four flame holders were used in this investigation, the details of which are shown in figure 3. The following table lists the number of annular rings, the gutter widths, and the blockages for each of the flame holders:

Flame holder	Number of rings	Gutter width, in.	Blockage, percent[1]
1	1	2.50	23
2	2	1.50	29
3	3	1.50	48
4	3	.75	29

[1]Based on combustion-chamber cross-sectional area.

Instrumentation

Measurements of pressure and temperature were taken at various stations along the burner, and the table in figure 1(b) lists the types and numbers of probes and orifices at each of the measuring stations. More specific details of the instrumentation at some of the stations are shown in figure 4.

Twenty-five Franz-type thermocouples were located at station 2 in order that the afterburner inlet total temperature could be recorded (fig. 4(a)).

At the burner inlet (station 4) 26 total-pressure probes, four stream static probes, and eight wall static orifices were located as shown in figure 4(b). At the burner outlet (station 5) 12 total-pressure

probes in a water-cooled survey rake were located as shown in figure 4(c), and one wall-static orifice was located at the nozzle outlet (station 7).

PROCEDURE

The air flow was set and maintained constant for a given series of runs by a choked valve in the air supply line upstream of the test facility, as shown in figure 1(a). When the air flow had been set, the exhaust nozzle was unchoked, thereby raising the burner-inlet pressure and lowering the inlet velocity. The afterburner was then ignited at a burner fuel-air ratio of approximately 0.050 by use of a torch-type ignitor located ahead of the flame holder, as shown in figure 1(b). Once ignition of the afterburner was completed, the ignitor was turned off and the exhaust nozzle was choked by decreasing the exhaust pressure. With the exhaust nozzle choked and the air flow set, runs were made at different fuel flows to vary fuel-air ratio. The fuel-air ratio range covered was from lean blow-out to rich blow-out, or to a fuel-air ratio of about 0.10, whichever occurred first.

Isothermal pressure drops (afterburner inoperative) at different inlet velocities were determined by changing exhaust pressure with an unchoked exhaust nozzle.

Stability limits were determined by flame extinction as observed through the quartz window in the wall of the burner. At the instant of blow-out, fuel flow and burner exit total pressure were recorded to permit definition of the stability limits and computation of the combustion efficiency at the stability limit. Afterburner air flow (actually air flow plus preheater fuel flow) for a given inlet-air supply valve setting was determined from total-pressure measurements at the burner exit with no burning and with the exhaust nozzle choked. The exhaust nozzle throat area was known, and an assumed flow coefficient was used in the computation.

The ratio of afterburner exit to inlet temperature was calculated using the ratio of afterburner exit total pressure with burning to that for nonburning with the nozzle choked, and combustion efficiency was taken as the ratio of actual afterburner temperature rise to the ideal temperature rise at the same fuel-air ratio. The ideal temperature rise was obtained from an ideal temperature rise curve in which dissociation was taken into account. Computational procedures used in determining afterburner temperature ratio and combustion efficiency are given in reference 1.

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The fuel used for this investigation was MIL-F-5624A grade JP-4, which had a heating value of 18,725 Btu per pound and a hydrogen-carbon ratio of 0.172.

RESULTS AND DISCUSSION

Inasmuch as this investigation was concerned primarily with the effects of flame-holder geometry on afterburner performance, no changes were made in either the fuel-injection system or diffuser throughout the investigation. The fuel-injection system was originally designed to give, as nearly as practicable, a uniform fuel-air distribution. Typical fuel-air distributions and diffuser exit velocity profiles may be found in reference 1.

Performance data obtained with the four flame-holder configurations are presented in figures 5 to 8, wherein combustion efficiency, burner inlet total pressure, burner inlet velocity, and burner total-pressure loss are plotted against fuel-air ratio. Because of the fixed-area exhaust nozzle, the burner inlet velocity varied from about 500 to 600 feet per second as the fuel-air ratio varied from about 0.03 to 0.10. Variation in burner air flow (from about 8.2 to about 21.7 lb/sec) and fuel-air ratio caused over-all variation in burner inlet total pressure from about 430 to 1300 pounds per square foot absolute. The data presented in this report are a continuum of those reported in reference 1 and are subject to about the same inaccuracies. As pointed out in reference 1, combustion efficiency experimental errors could conceivably be as high as 5 to 10 percentage points. In subsequent sections some of the conclusions are drawn from data trends which fall within this band of experimental error. However, because of the consistent trends of the data presented, the conclusions are believed to be valid.

Effect of Number of Annular V-Gutters

on Combustion Efficiency

The performance data of the four configurations shown in figures 5 to 8 were cross-plotted for fuel-air ratios of 0.05, 0.06, and 0.07 and are presented in figures 9 and 10 to illustrate the effect of the number of annular V-gutters on afterburner combustion efficiency.

Flame holders with different blockages. - In figure 9, variation of combustion efficiency with burner inlet total pressure is presented for a 1-ring flame holder having 23 percent blockage, a 2-ring flame holder having 29 percent blockage, and a 3-ring flame holder having 48 percent blockage. Maximum afterburner inlet velocity variation over the range of fuel-air ratios and pressures shown in figure 9 was from about 480 to

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570 feet per second. It can be seen that at a given burner inlet total pressure increasing the number of rings increases the combustion efficiency; for example, at a burner inlet total pressure of 700 pounds per square foot absolute, the 3-ring, 48-percent blockage flame holder had a combustion efficiency which was 16 percentage points higher than the 1-ring, 23-percent blockage flame holder. Although there was an increase in blockage with increasing number of gutters, the increasing efficiency is felt to be a result primarily of increasing number of gutter rings or stable flame sources from which flame could propagate into the unburned fuel-air mixture flowing through the burner. Consideration of the qualities of the combustion mechanism as they are generally understood in burners of the type investigated will serve to explain this.

First, consider a simplified burner as illustrated in the following sketch:
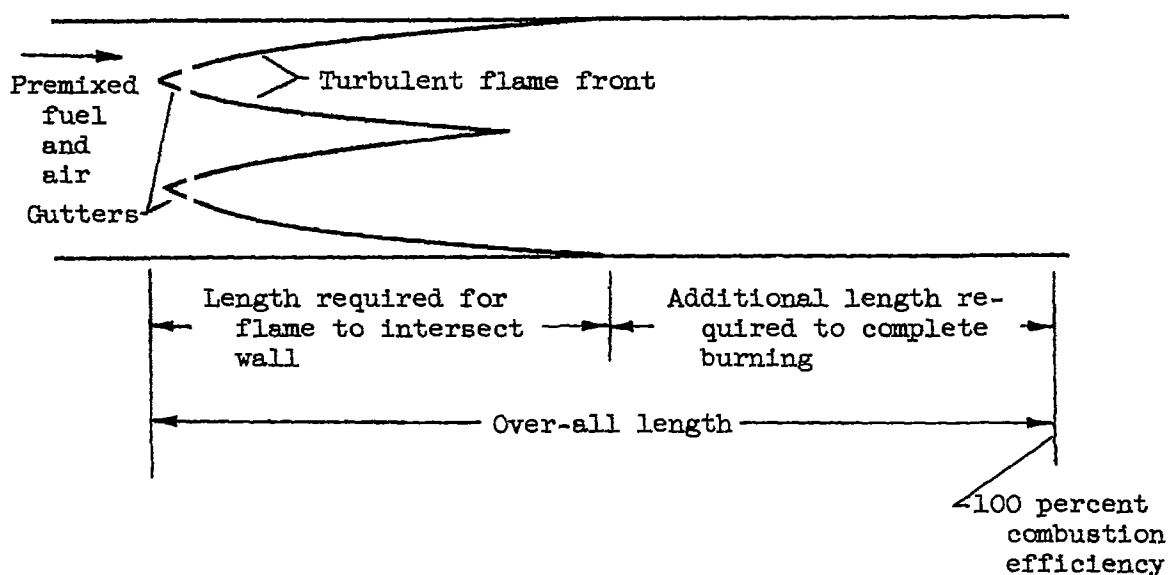
Recirculating burned gases immediately behind the flame holders serve as a source of ignition and from these sources flame propagates at a relatively slow rate into the fuel-air mixture as it flows downstream. If the process were ideal the flame fronts would be continuous and would possess the characteristics of a laminar flame. There would be no reaction upstream of the flame front, while immediately downstream of the flame front the reaction would be complete (local combustion efficiency, 100 percent). If the flame front traversed the entire fuel-air mixture as illustrated in the sketch, the over-all combustion efficiency would be 100 percent.

In an actual combustor, however, a clearly defined laminar flame front is not present (ref. 2). Pockets of unburned mixture appear to be carried downstream beyond a flame front which has a turbulent appearance. Even though the apparent flame front might traverse the entire fuel-air mixture to the burner wall, an additional length of combustor is required to complete the burning of the fuel-air mixture in these pockets. In practice, there is no longer a 100 percent completed reaction immediately downstream of the flame front. The over-all combustion efficiency might still approach 100 percent, however, if an additional length of burner were provided as shown in the preceding sketch to complete the burning of the fuel-air mixture pockets.

Consider a similar burner of identical length but having only one gutter for a flame source, as illustrated in the following sketch:

Premixed fuel
and air

Gutter

Turbulent flame front

Additional length available to complete fuel pocket burning

Length required for flame to intersect wall

Over-all length

Less than 100 percent combustion efficiency
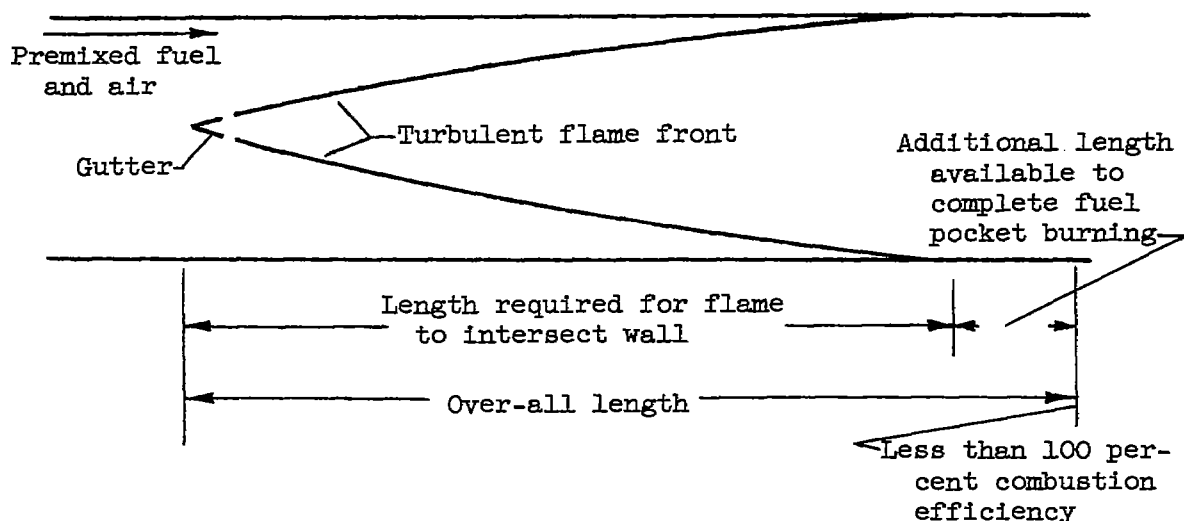
A loss in combustion efficiency must occur since the increment of available burner length required for flame propagation is increased, and this in turn reduces the increment of length available for pocket burning. Such reasoning suggests that for an actual burner of limited length, increasing the number of flame-holding gutters can increase the combustion efficiency.

Flame holders with constant blockage. - Data obtained illustrating the effect of increasing the number of annular V-gutters (from 2 to 3) while maintaining the over-all blockage constant at 29 percent are presented in figures 10(a) to 10(c) for fuel-air ratios of 0.05, 0.06, and 0.07. Again, combustion efficiency is plotted against burner inlet total pressure. It can be seen that at a burner inlet total pressure of 1100 pounds per square foot absolute as much as an 8 percentage point improvement was obtained by the 3-ring, V-gutter flame holder over the

2-ring, V-gutter flame holder. However, at a burner inlet total pressure of about 600 pounds per square foot absolute as much as a 9 percentage point inferiority was obtained with the 3-ring, V-gutter flame holder. The low-pressure inferiority of the 3-ring flame holder seemed to be related to an unsteadiness of flame which was observed visually by means of a quartz window in the wall of the burner. The 3-ring, V-gutter flame holder had 0.75-inch-wide annular V-gutters supported by 1.5-inch-wide radial V-gutters, whereas all elements of the 2-ring flame holder were 1.5 inches wide. As the pressure decreased the flame seated on the 0.75-inch annular V-gutters of the 3-ring flame holder started flickering and periodically blew out. The burning behind the 1.5-inch-wide supporting radial V-gutters remained bright and steady. For the 2-ring, 1.5-inch-wide V-gutter flame holder, however, the flame seating on both the annular and the radial V-gutters remained bright and steady as the pressure decreased. References 2 and 4 show that flame holders having a narrow gutter width have poorer stability limits than those having a wide gutter width. It thus appears that the flame periodically blew out on the 0.75-inch gutters because they were operating below their stability limits, but the flame burned steadily on the 1.5-inch gutters because these were operating within their stability limits. As a result, below the pressure corresponding to the stability limit of the 0.75-inch gutters, the combustion efficiency of the 3-ring flame holder dropped off more rapidly than for the 2-ring flame holder.

A comparison of the performance of the two 3-ring flame holders at comparable conditions of operation (figs. 9 and 10) revealed that both had about the same combustion efficiency above a pressure of about 900 pounds per square foot. Thus, an increase in blockage from 29 percent to 48 percent gave no improvement in combustion efficiency so long as the 0.75-inch gutters of the 29 percent blockage flame holder were maintaining stable operation.

Effect of Gutter Width on Stability Limits

A comparison of the stability limits obtained with the four flame-holder configurations is shown in figure 11, where the burner outlet total pressure is plotted against the fuel-air ratio at blow-out. At a given fuel-air ratio, combustion could not be obtained at pressures below those defined by the curve for a particular flame holder. Both lean and rich stability limits, which define the range of operable fuel-air ratios, were determined for each flame holder. At a given burner outlet pressure the operable range of fuel-air ratios improved as the width of the annular flame-holder gutters increased from 0.75 inch to 2.5 inches, an effect in accord with that found in such other investigations as reference 2. The operable range of fuel-air ratios narrowed with decreasing pressure. The rate of deterioration of the lean stability limit with decreasing pressure was more pronounced for the flame holder with

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0.75-inch annular gutters than for the flame holders with 1.5- and 2.5-inch annular gutters. This peculiar characteristic may have been associated with the previously mentioned flickering flame observed at low pressures with the 3-ring, 29-percent blockage flame holder.

It should be noted that the stability limits for the 3-ring, 29-percent blockage flame holder probably do not represent true limits for 0.75-inch-wide gutter flame holders. The 1.5-inch interconnecting gutters used on the 3-ring, 29-percent blockage flame holder apparently stabilized flame at some severe operating conditions where flame could not have been stabilized on the 0.75-inch gutters alone.

Effect of Flame-Holder Blockage on Pressure Drop

On the basis of the combustion results obtained in this investigation, it appears desirable to have as many annular gutters as possible to obtain high combustion efficiency and yet have wide gutters to obtain good combustion performance at low pressure. Combining the features of multiple-wide gutters into a single design, however, generally leads to high blockages and to resulting high internal losses during nonburning operation which compromise aircraft cruise performance. The effect of burner inlet velocity and flame-holder geometry on nonburning total-pressure loss is presented in figure 12 for the four flame holders investigated. As the burner inlet velocity increased the nonburning total-pressure loss increased at an increasing rate. Also, it is to be noted that one curve could be drawn through the data points for both 29-percent blockage flame holders even though each contained a different number of annular gutters of different widths. In addition, at any given velocity nonburning total-pressure loss increased as flame-holder blockage increased. The effect of flame-holder blockage on nonburning total-pressure loss is shown more clearly in figure 13, a cross-plot of the data of figure 12. Curves of pressure drop against blockage are shown for burner inlet velocities of 400, 500, and 600 feet per second (burner inlet Mach numbers of 0.20, 0.25, and 0.30, respectively). It can be seen in figure 13 that at low flame-holder blockages, low nonburning total-pressure losses are obtained. As flame-holder blockages increase, nonburning total-pressure losses rise rapidly; therefore, in order to keep the burner total-pressure loss and consequent thrust loss during nonafterburner operation low (2 percent or less), flame-holder blockages greater than 35 percent are not advisable for burner inlet velocities greater than 500 feet per second.

CONCLUDING REMARKS

An investigation was conducted in a 26-inch-diameter afterburner test rig to determine the effect of the number and width of flame-holder

annular V-gutters on afterburner performance. One 1-ring, one 2-ring, and two 3-ring flame holders were investigated from a fuel-air ratio of about 0.03 to a fuel-air ratio of about 0.10. For these conditions variations in afterburner inlet total pressures from about 450 to 1300 pounds per square foot absolute were obtained.

For flame holders composed of annular V-gutters, the combustion efficiency increased as the number of annular V-gutters increased. A 3-ring, 48-percent blockage flame holder had 15 to 20 percentage points higher combustion efficiency than a 1-ring, 23-percent blockage flame holder for burner inlet total pressures from about 600 to 800 pounds per square foot absolute over a range of fuel-air ratios from 0.05 to 0.08. At burner inlet total pressures above about 700 pounds per square foot absolute, both 3-ring V-gutter flame holders (one 29-percent blockage and one 48-percent blockage) were superior to the 2-ring, V-gutter flame holder.

Gutter widths of 1.5 inches or more were found to be necessary under the conditions of operation for good low pressure performance. Below a burner inlet total pressure of about 700 pounds per square foot absolute, a 2-ring, 1.5-inch-wide V-gutter flame holder was superior to a 3-ring, 0.75-inch-wide V-gutter flame holder. There was local blow-out of the flame seating on the 0.75-inch V-gutters, while the flame seating on the 1.5-inch V-gutters remained bright and steady.

A large number of wide rings, however, generally lead to high blockage flame holders, which in turn result in high nonburning total-pressure losses. If pressure losses in excess of 2 percent are to be avoided, flame-holder blockages should not exceed about 35 percent for burner inlet velocities greater than 500 feet per second.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, March 30, 1954

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1. Nakanishi, S., Velie, W. W., and Bryant, L.: An Investigation of the Effects of Flame-Holder Gutter Shape on Afterburner Performance. NACA RM E53J14, 1954.

2. Scurlock, A. C.: Flame Stabilization and Propagation in High-Velocity Gas Streams. Meteor Rep. 19, M. I. T., May 1948. (Contract NOrd 9661.)

3. Friedman, J., Bennet, W. J., and Zwick, E. B.: The Engineering Application of Combustion Research to Ram-Jet Engines. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co., 1953, pp. 756-764.

4. Renas, Paul E., and Jansen, Emmert T.: Effect of Flame-Holder Design on Altitude Performance of Louvered-Liner Afterburner. NACA RM E53H15, 1953.

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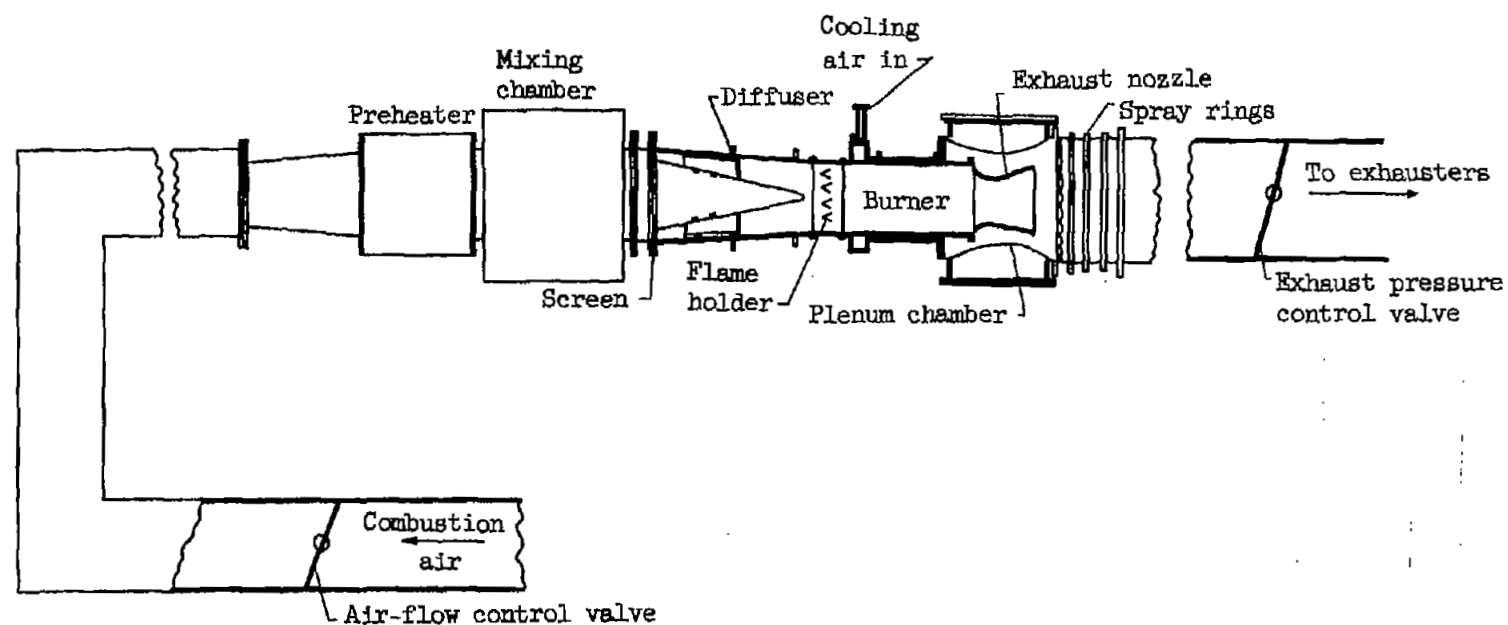
(a) General arrangement.

Figure 1. - Schematic layout of simulated afterburner test rig.

Station 1 Diffuser inlet

2 3 Fuel injection

4 Burner inlet

5 6 7 Burner Nozzle Nozzle outlet throat outlet

Preheater

Mixing chamber

33.25 26.95

32 6 22.5 61.5 8.1 24.3

Support struts

Air

Fuel nozzle

Thin single jet

Spark plug

Quartz window

25.75

13 60.5 67.5

5 48 5 28.9

CD-3399
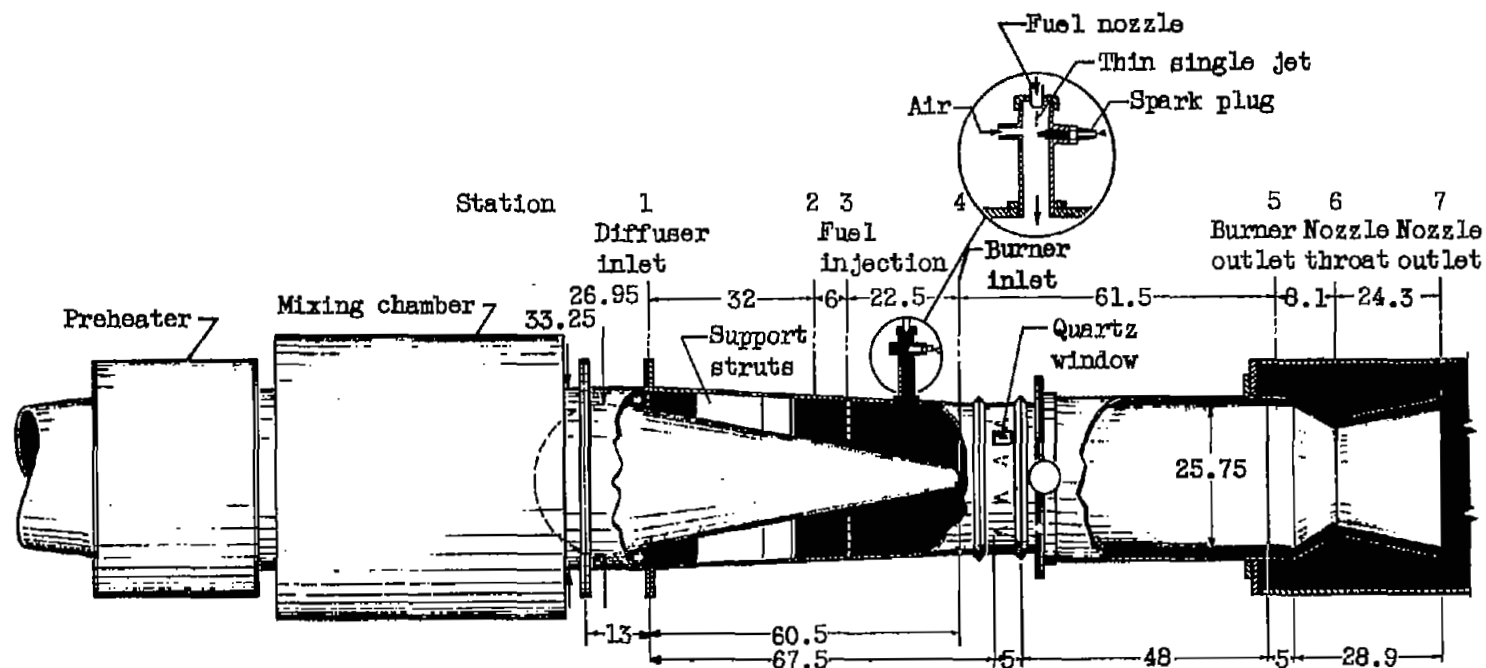
Instrumentation

[a]Station	Total-pressure tubes	Static-pressure tubes	Wall static orifices	Thermo-couples
2	--	-	-	25
4	26	4	8	--
5	12	-	2	--
7	--	-	1	--

[a]Instrumentation at stations 1, 3, and 6 not used in computations.

(b) Burner details. (Dimensions are in inches.)

Figure 1. - Concluded. Schematic layout of simulated afterburner test rig.
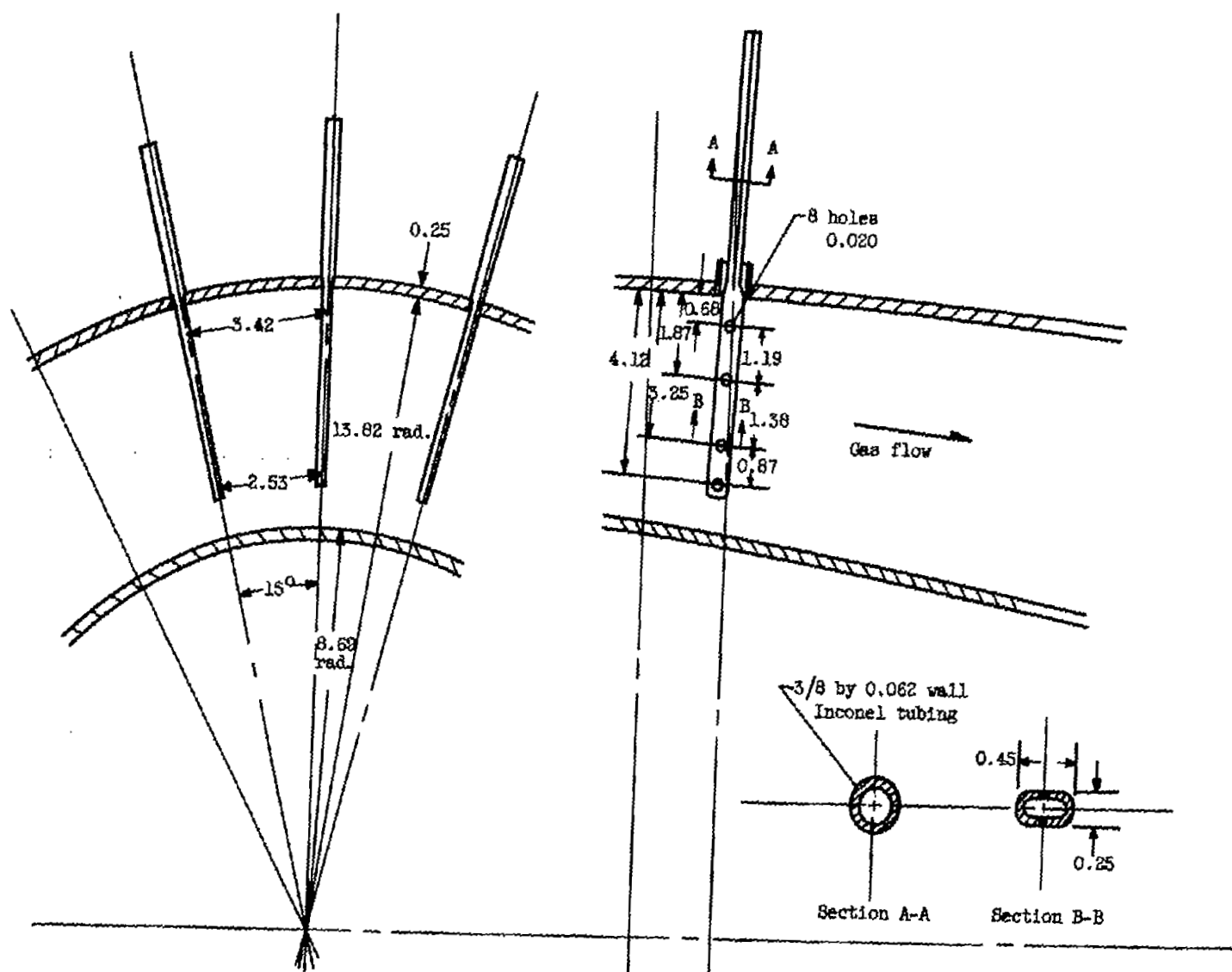
Figure 2. - Afterburner fuel injection system (station 5). (Dimensions are in inches.)

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Flame holder 1

1-ring, 23 percent blockage
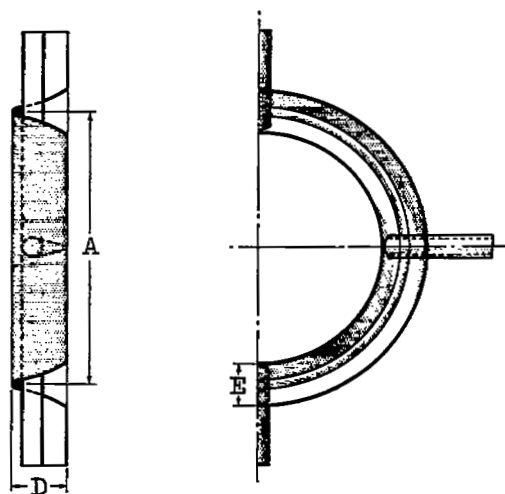
Flame holder 2

2-ring, 29 percent blockage
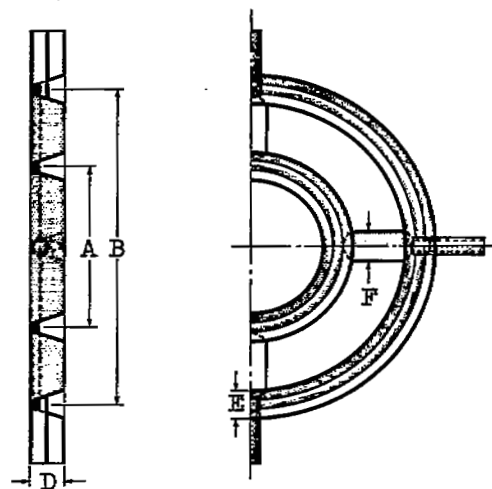
Flame holder 3

3-ring, 48 percent blockage
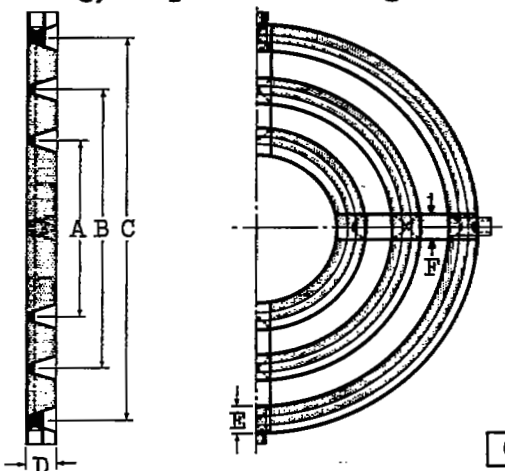
Flame holder 4

3-ring, 29 percent blockage
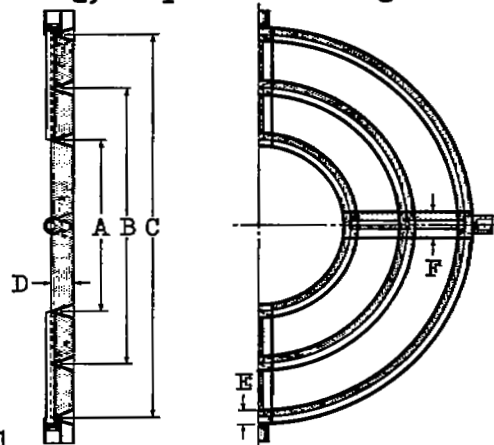
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Flame holder	Type of gutters	Dimensions, in.					
		A	B	C	D	E	F
1	cam-bered	15.92			2.88	2.50	
2	V	9.50	18.50		1.57	1.50	1.50
3	V	10.25	16.45	22.65	1.57	1.50	1.50
4	V	10.13	16.38	22.64	1.25	0.75	1.50

Figure 3. - Flame-holder details.

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Franz-type thermocouple tip

13.889 rad.
13.045
12.139
11.154
10.076

14.3 rad.

9.55 rad.

90°

45°

45°

90°

63°

37°

64°

119°

77°

(a) Station 2.

○   Total-pressure probe
⊙   Stream static-
        pressure probe
●   Wall static-pressure
        tap
⊗   Thermocouple

100°   64°

12.87 rad.

167°

8°

12.43 rad.
11.43
10.43
9.43
8.43
7.43
6.43
5.43
4.43
3.43
2.43
1.43
.43

4.87 rad.

6.87

8.87

10.87

215°

242°

303°

335°
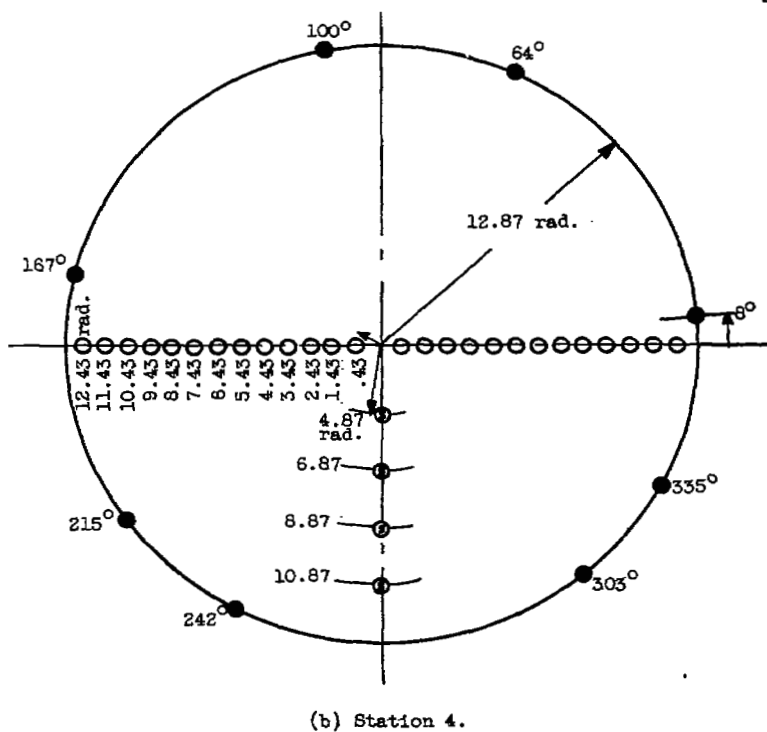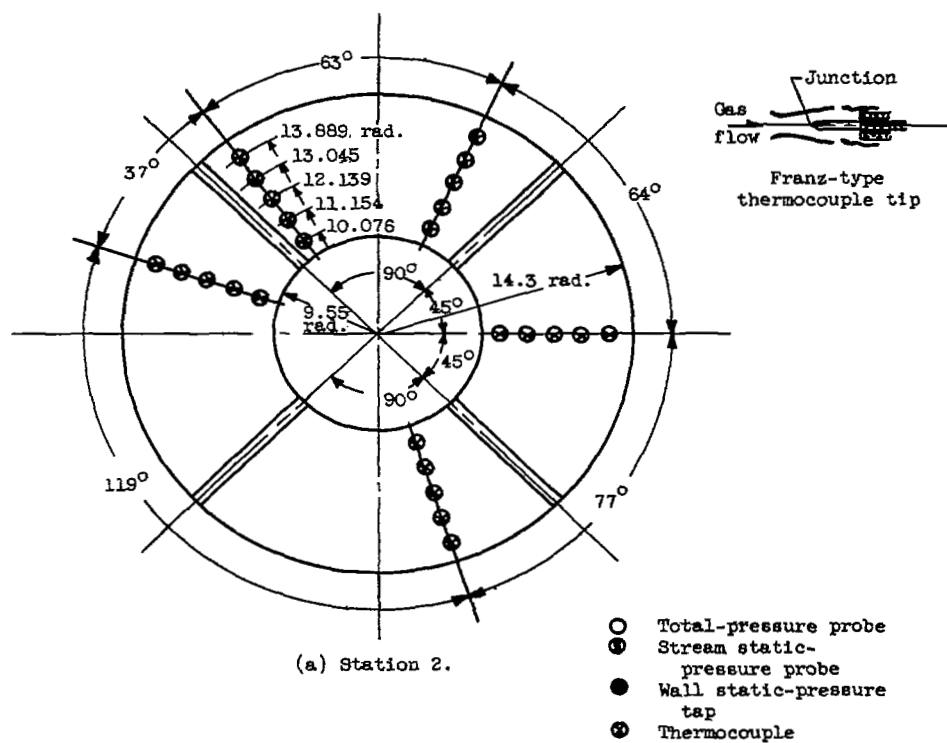
(b) Station 4.

Figure 4. - Schematic diagram of instrumentation stations.
(View looking downstream.)
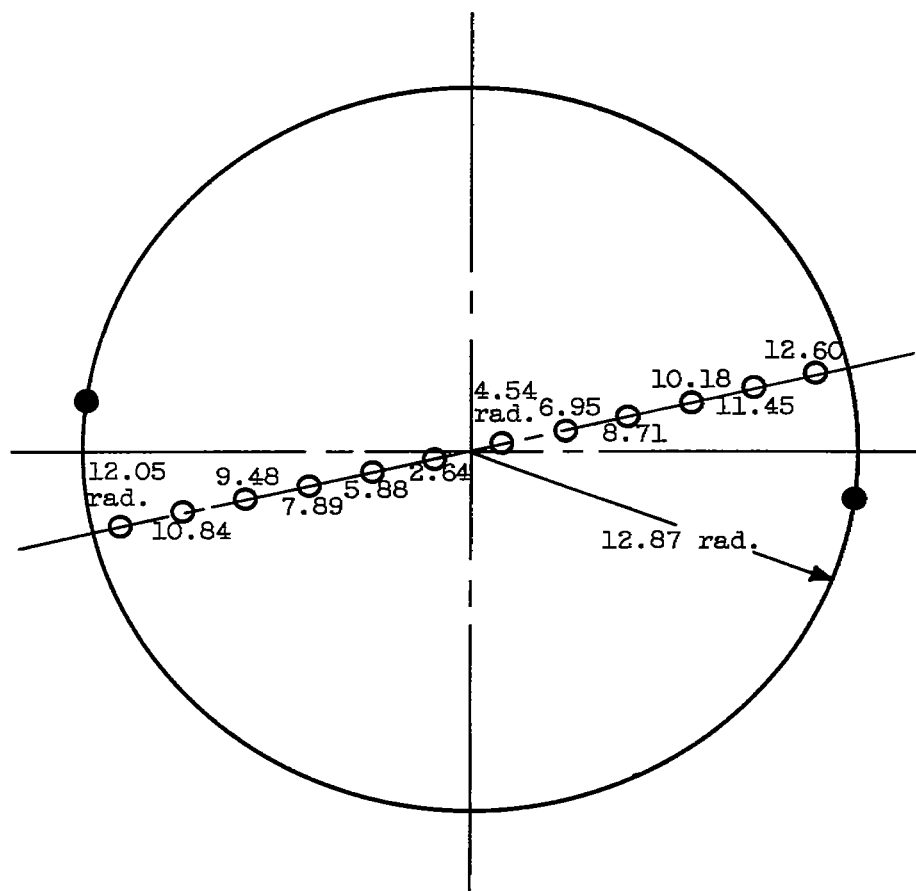
(c) Station 5.

Figure 4. - Concluded. Schematic diagram of instrumentation
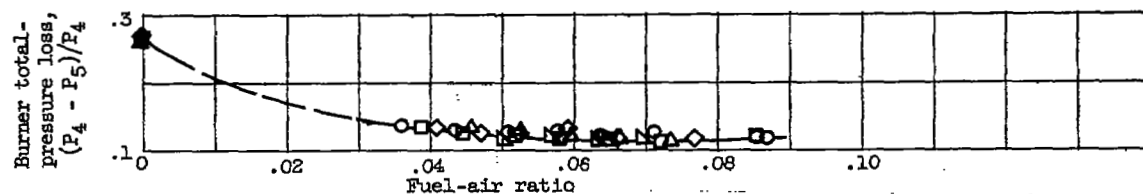   stations. (View looking downstream.)
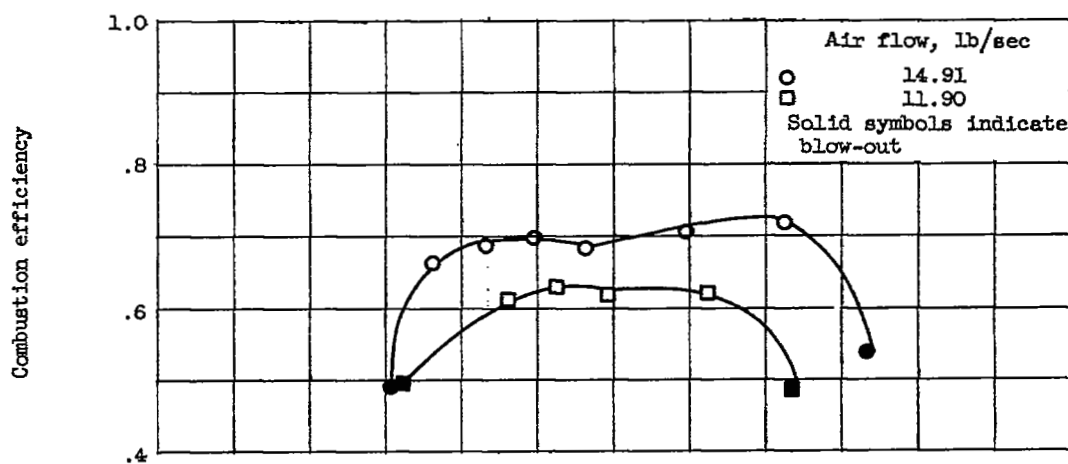
(a) Combustion efficiency.
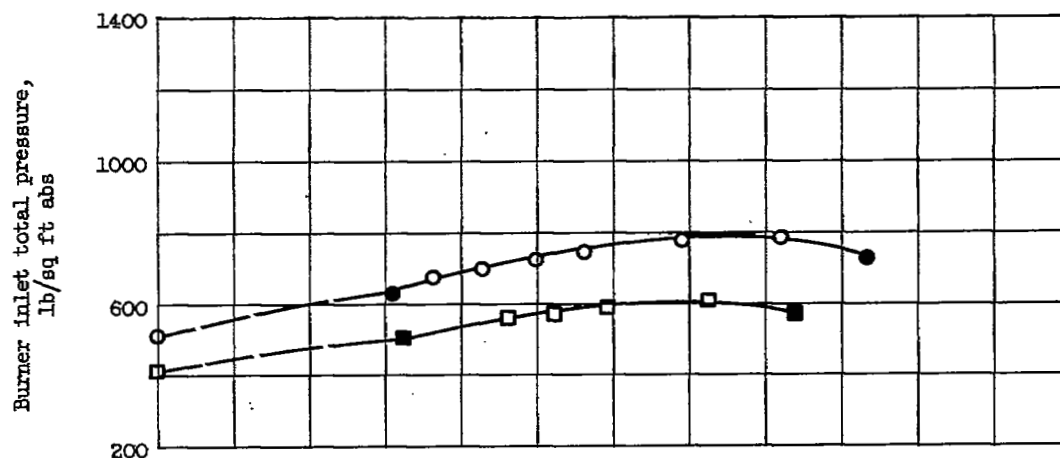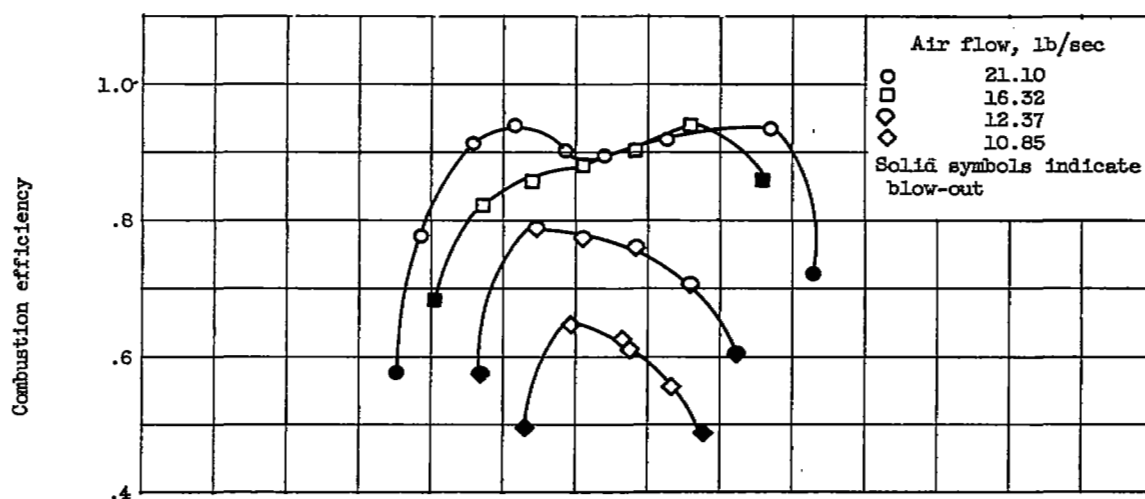
(b) Burner inlet total pressure.
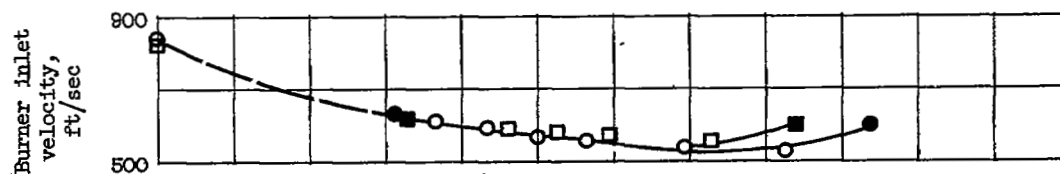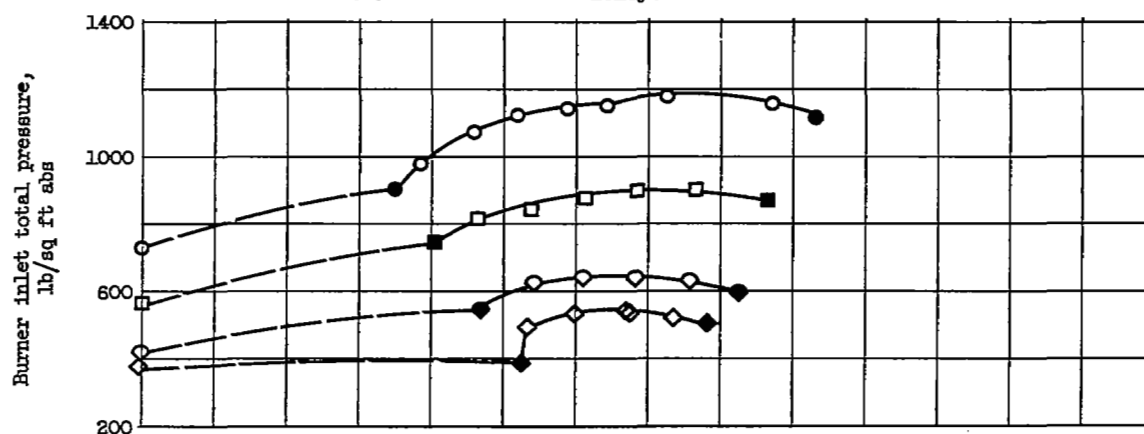
(c) Burner inlet velocity.
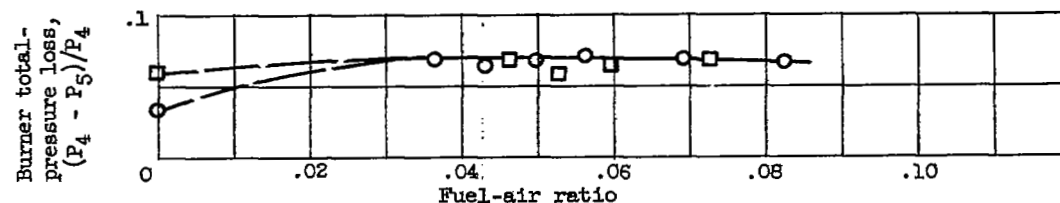
(d) Burner total-pressure loss.

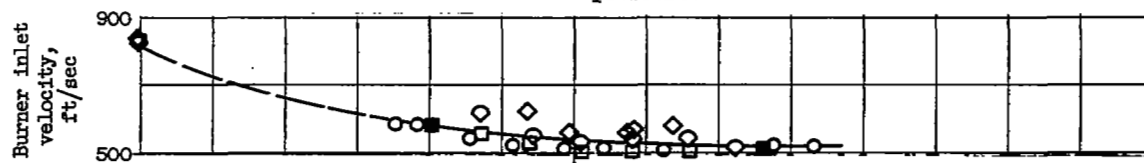Figure 5. - Performance of flame holder configuration 1. Single <-shaped ring gutter; width, 2.5 inches; over-all blockage, 23 percent.
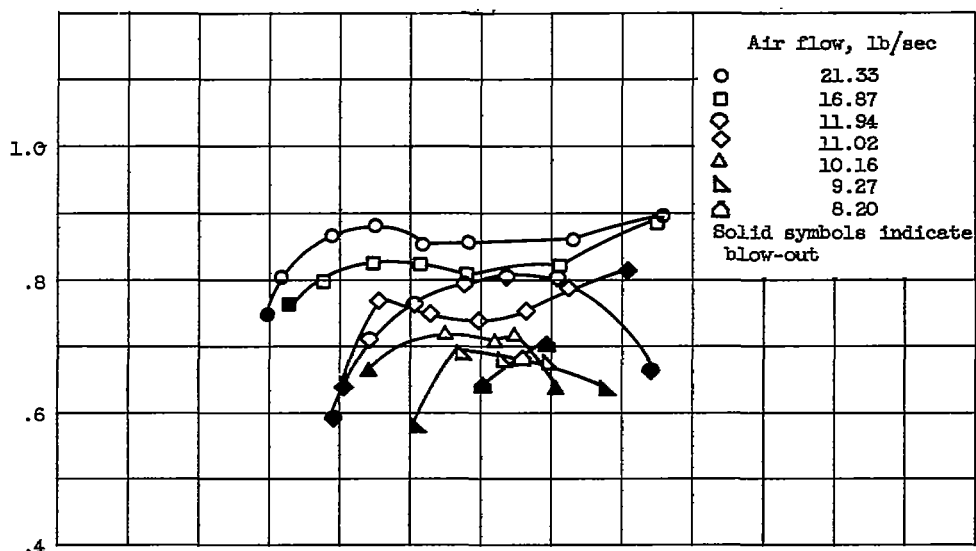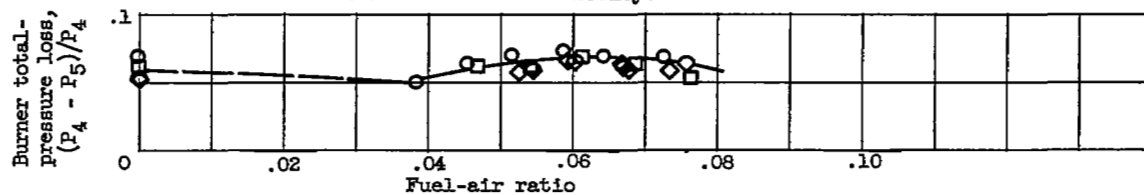
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(a) Combustion efficiency.

(b) Burner inlet total pressure.

(c) Burner inlet velocity.

(d) Burner total-pressure loss.

Figure 6. - Performance of flame holder configuration 2. Two V-shaped ring
gutters; width, 1.5 inches; over-all blockage, 29 percent.
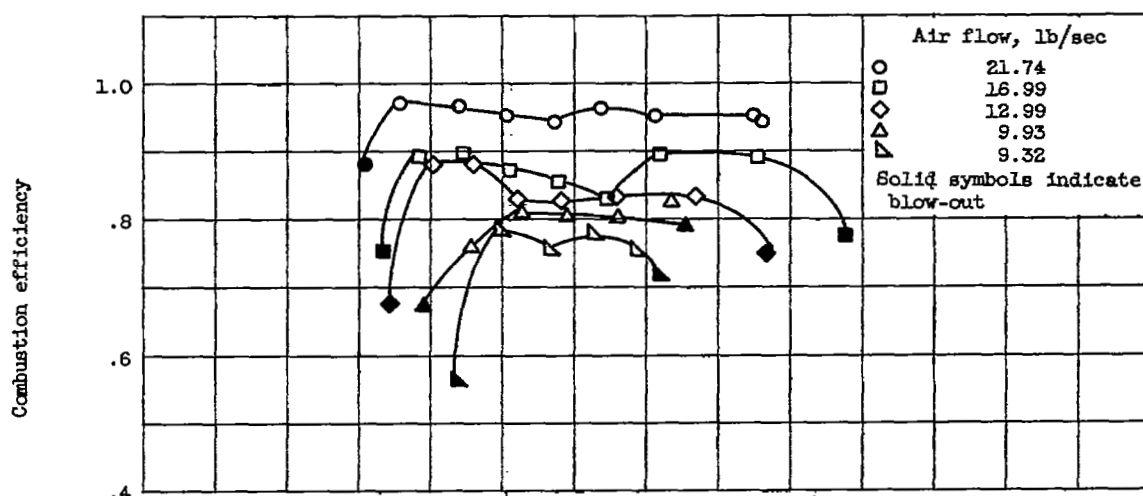
(a) Combustion efficiency.
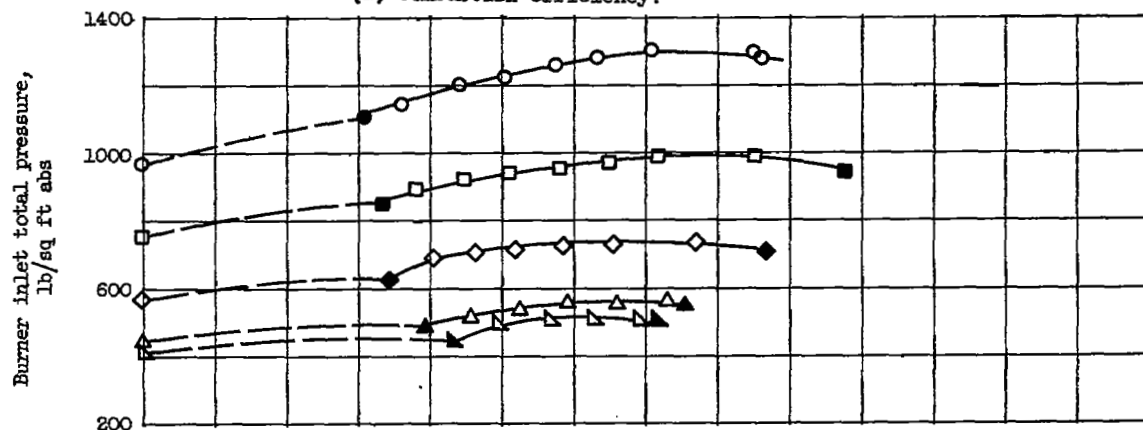
(b) Burner inlet total pressure.
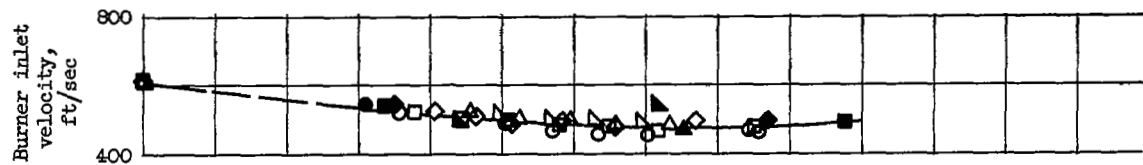
(c) Burner inlet velocity.

(d) Burner total-pressure loss.

Figure 7. - Performance of flame holder configuration 3. Three V-shaped
ring gutters; width, 1.5 inches; over-all blockage, 48 percent.

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(a) Combustion efficiency.

(b) Burner inlet total pressure.

(c) Burner inlet velocity.

(d) Burner total-pressure loss.

Figure 8. - Performance of flame holder configuration 4. Three V-shaped
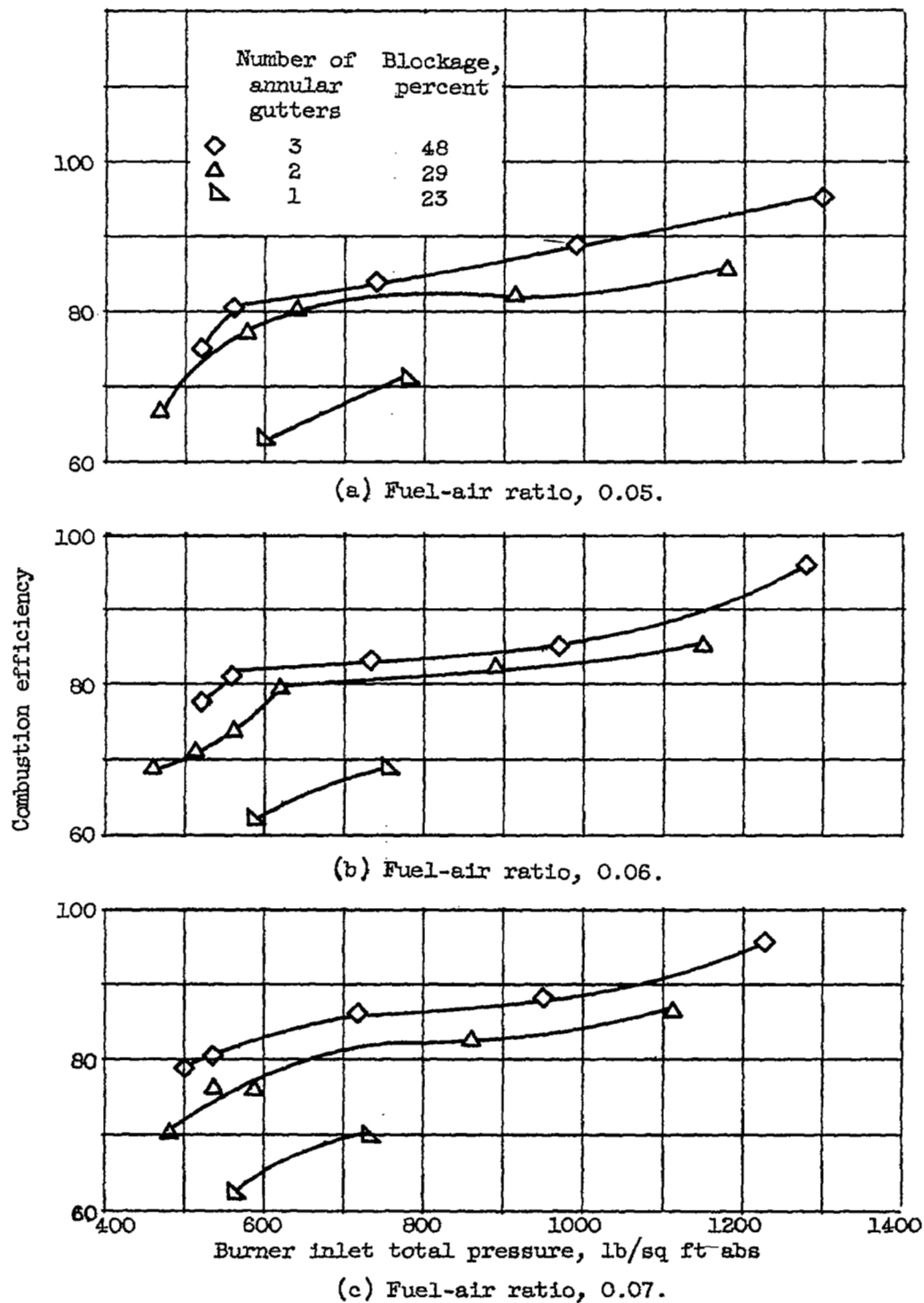ring gutters; width 0.75 inch; over-all blockage, 29 percent.

(a) Fuel-air ratio, 0.05.

(b) Fuel-air ratio, 0.06.

(c) Fuel-air ratio, 0.07.

Figure 9. - Effect of number of annular V-gutters on combustion efficiency for flame holders of different blockages.

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(a) Fuel-air ratio, 0.05.

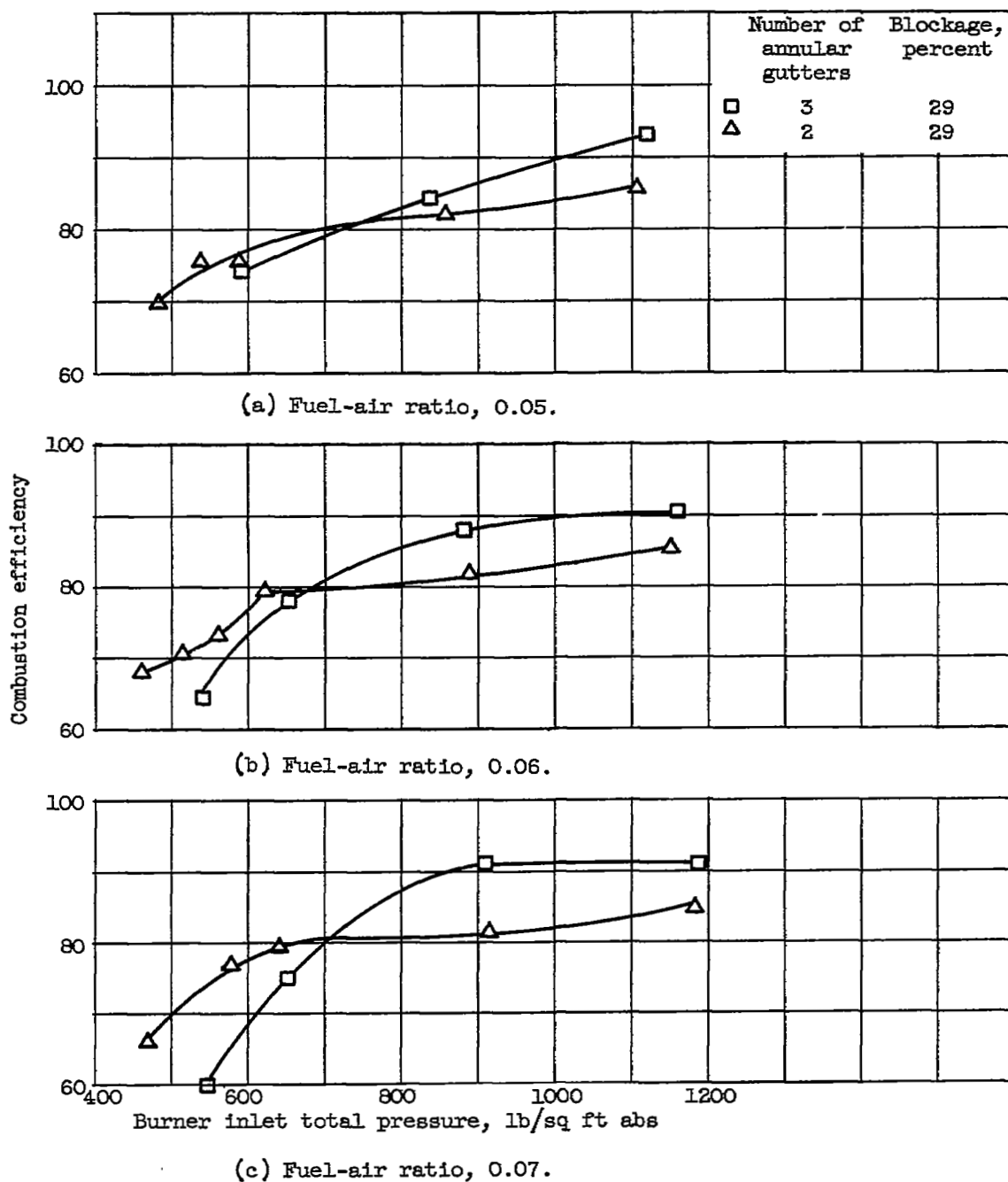(b) Fuel-air ratio, 0.06.

(c) Fuel-air ratio, 0.07.

Figure 10. - Effect of number of annular V-gutters on combustion efficiency for flame holders of equal blockages.

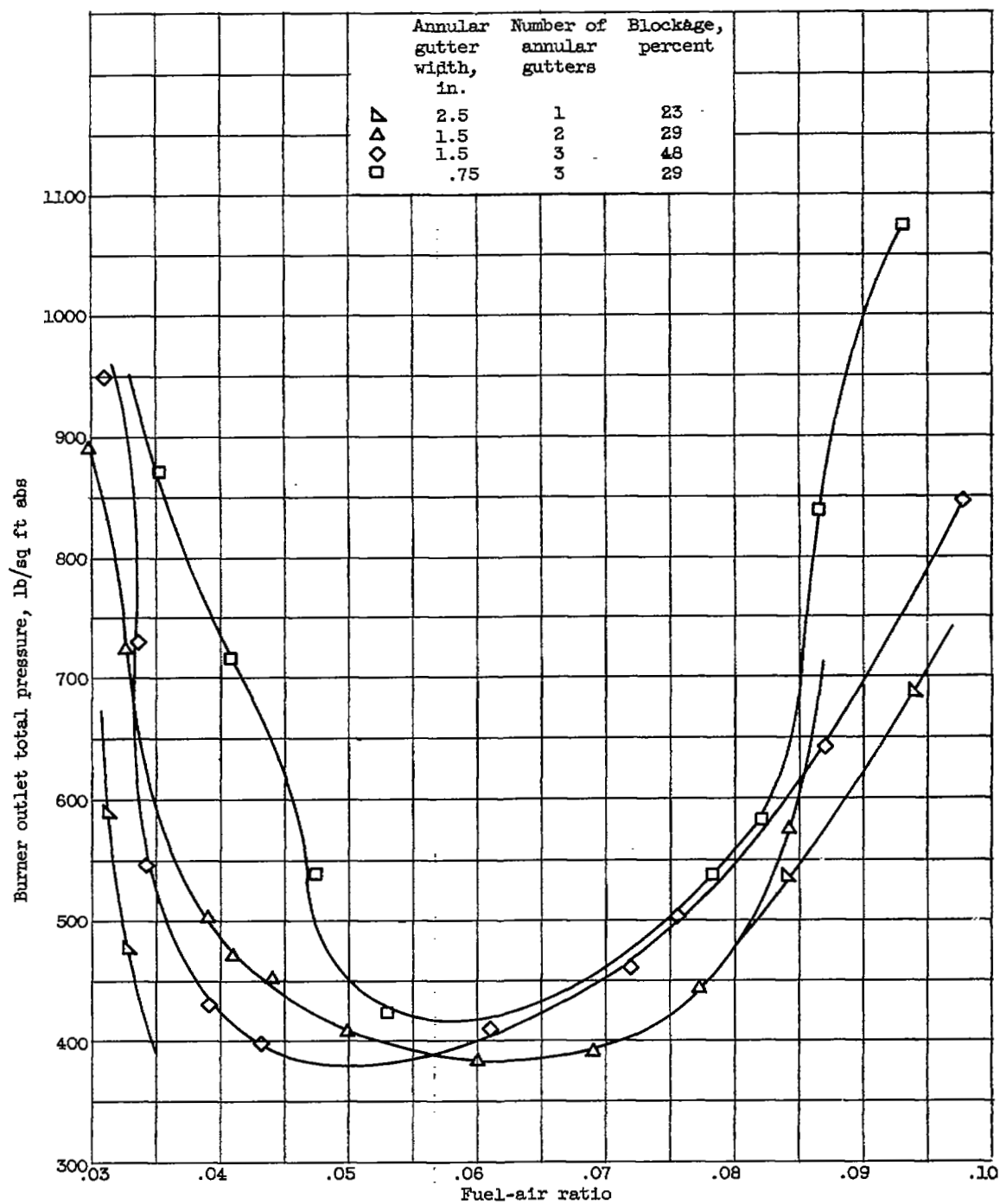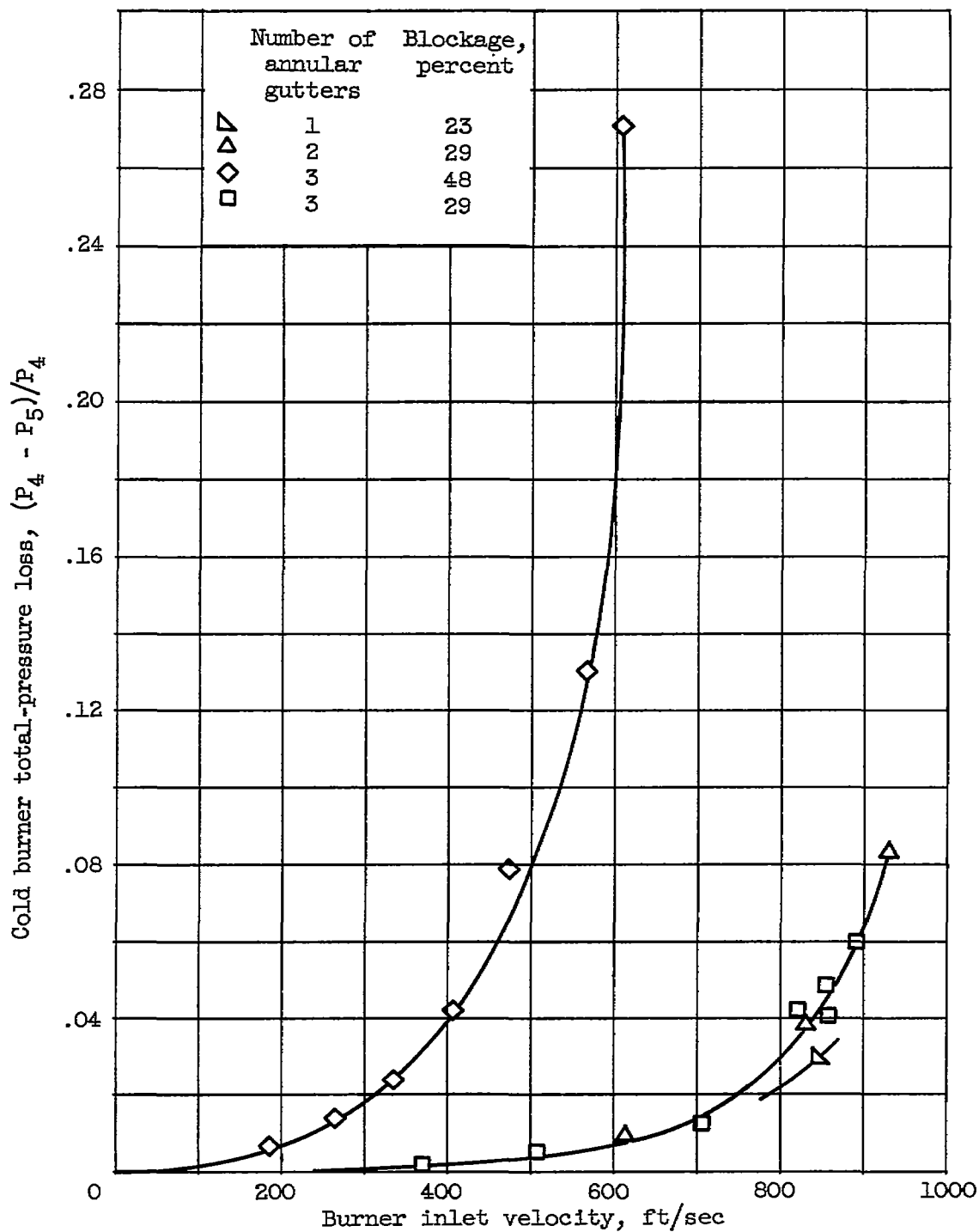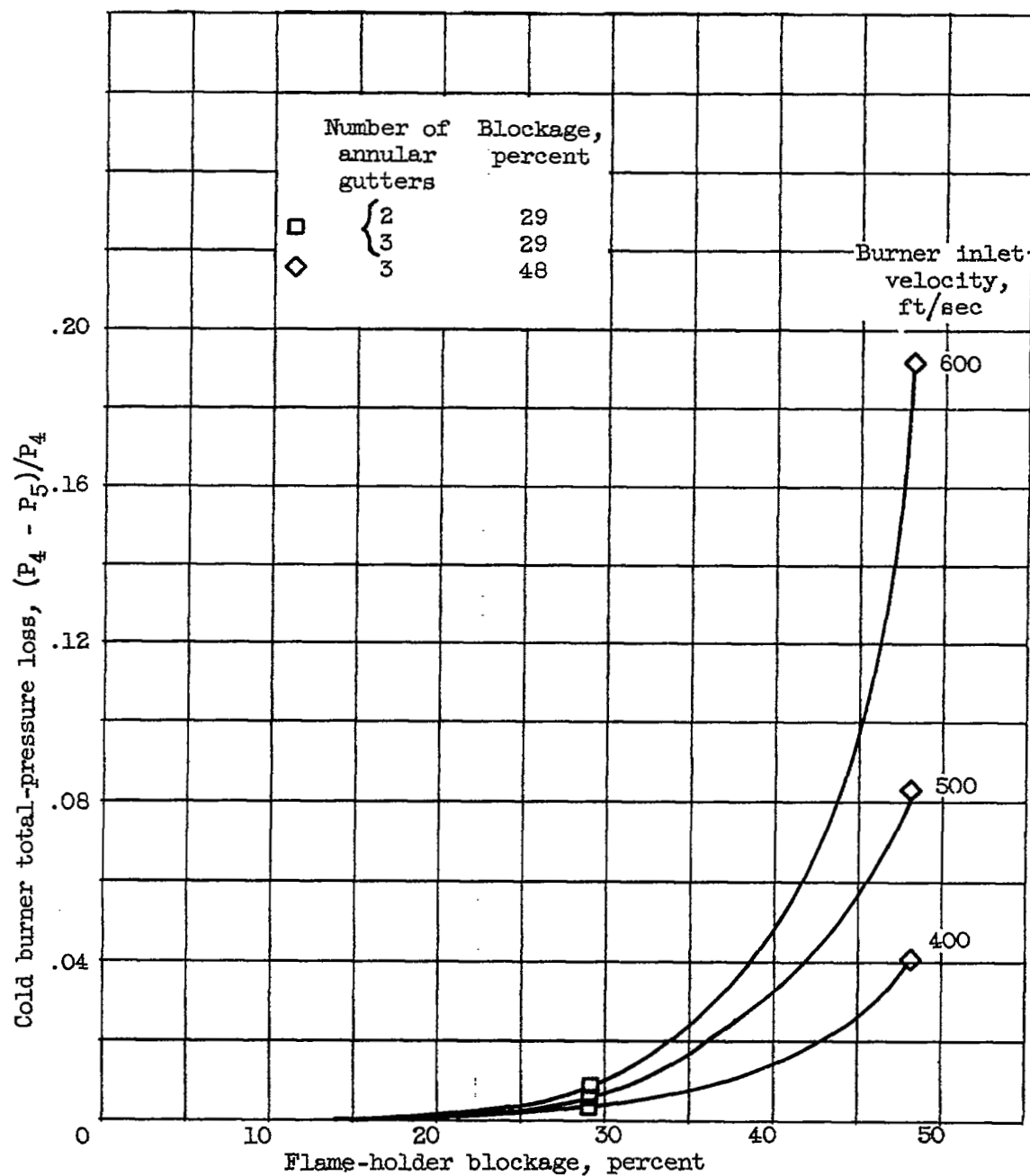Figure 11. - Effect of gutter width on afterburner stability limits.

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Figure 12. - Effect of burner inlet velocity on nonburning total-
pressure loss.

Figure 13. - Effect of flame-holder blockage on nonburning total-pressure loss.